Growth Variability of Scots Pine (Pinus sylvestris) along a West-East Gradient across Northern Fennoscandia: A Dendroclimatic Approach

Authors: Macias, Marc, Macias, Marc, Macias, Marc, Macias, Marc, Timonen, Mauri, et al.

Source: Arctic, Antarctic, and Alpine Research, 36(4) : 565-574

Published By: Institute of Arctic and Alpine Research (INSTAAR), University of Colorado

URL: https://doi.org/10.1657/1523-0430(2004)036[0565:GVOSPP]2.0.CO;2

Arctic, Antarctic, and Alpine Research, Vol. 36, No. 4, 2004, pp. 565–574

Growth Variability of Scots Pine (*Pinus sylvestris*) along a West-East Gradient across Northern Fennoscandia: A Dendroclimatic Approach

Marc Macias†‡$*
Mauri Timonen†
Andreas J. Kirchhefer§
Markus Lindholm#
Matti Eronen and*
Emilia Gutiérrez‡

*Geology Department, Division of Geology and Palaeontology, University of Helsinki, Finland.
†Finnish Forest Institute, Rovaniemi Research Station, Eteläranta 55, 96300 Rovaniemi, Finland.
‡Department of Ecology, University of Barcelona, Barcelona, Catalonia, Spain.
§Department of Biology, University of Tromsø, Tromsø, Norway.
#Department of Biology, Faculty of Natural Sciences, University of Joensuu, Finland.
$Corresponding author: Marc Macias Fauria, marc.macias@helsinki.fi

Abstract

We performed a spatiotemporal analysis of a network of 21 Scots pine (*Pinus sylvestris*) ring-width chronologies in northern Fennoscandia by means of chronology statistics and multivariate analyses. Chronologies are located on both sides (western and eastern) of the Scandes Mountains (67°N–70°N, 15°E–29°E). Growth relationships with temperature, precipitation, and North Atlantic Oscillation (NAO) indices were calculated for the period 1880–1991. We also assessed their temporal stability. Current July temperature and, to a lesser degree, May precipitation are the main growth limiting factors in the whole area of study. However, Principal Component Analysis (PCA) and mean interseries correlation revealed differences in radial growth between both sides of the Scandes Mountains, attributed to the Oceanic-Continental climatic gradient in the area. The gradient signal is temporally variable and has strengthened during the second half of the 20th century. Northern Fennoscandia Scots pine growth is positively related to early winter NAO indices previous to the growth season and to late spring NAO. NAO/growth relationships are unstable and have dropped in the second half of the 20th century. Moreover, they are noncontinuous through the range of NAO values: for early winter, only positive NAO indices enhance tree growth in the next growing season, while negative NAO does not. For spring, only negative NAO is correlated with radial growth.

Introduction

The north of Fennoscandia (Fig. 1) constitutes an excellent source of information for dendroclimatologists due to the clear response of tree growth to climate in the region. Control of annual growth by environmental factors, particularly climate, is strong and clearly discernible in areas where trees grow in marginal environments (Fritts, 1976). Scots pines (*Pinus sylvestris* L.) growing under extreme conditions in the northern timberline region are known to have a strong "common" signal, which is empirically linked to summer temperature forcing (mainly July) (Briffa et al., 1990; Lindholm, 1996).

Northern Fennoscandia extends from the shores of the north Atlantic Ocean in Norway in the west to the White Sea and Kola Peninsula in Russia in the east, and from the Arctic Circle in the south to the Barents Sea in the north. The Gulf Stream influences climate in the area, making it milder than in other regions at the same latitude.

Climate in the area is greatly influenced by the presence of the northeast Atlantic Ocean and the Scandes Mountains. Cool, moist Atlantic air masses are trapped along northern Norway by the high mountains very close to the coast. As a result, the climate is extraordinarily wet in that area, with precipitation up to 2500 mm yr^{-1}.

There is a gradient of continentality towards the east, enhanced by the presence of the mountains, which also create local montane climates in the Scandes (Barry, 1992). The climate east of the Scandes is rather continental. In the far north, continentality declines under the influence of the Arctic Ocean (Tuhkanen, 1980).

Few studies have been carried out using chronologies from both sides of the Scandes (Kirchhefer, 1999; Linderholm et al., 2003). Although tree-growth limiting factors are mainly related to summer temperature in the entire range, the growing season differs slightly from the east and continental side of the mountain range, where it is earlier and shorter (July, sometimes June) (Lindholm, 1996), to the Scandes and Atlantic coast, where the season is later and longer (July, August) and is influenced by more climatic parameters (Kirchhefer, 2001).

The North Atlantic Oscillation (NAO) is a large-scale seesaw between the Icelandic Low and the Azores High (Van Loon and Rogers, 1978). It is one of the Northern Hemisphere's major multiannual climate fluctuations (Appenzeller, 1999). NAO indices are calculated by computing the difference between the SLP (sea level pressure) in these two areas (SLP Azores–SLP Iceland). NAO is most clearly expressed during the winter (Van Loon and Rogers, 1978).

High positive NAO situations imply a large SLP difference between the two air masses. When the gradient of pressure is large, there is an increase in the western (maritime) winds in northern Europe, where winters are wetter and milder. The stronger the wind, the more of the Gulf Stream's heat is delivered to Eurasia. A negative NAO situation brings a relaxation of the western winds over northern Europe (less Gulf Stream influence), with a consequently drier and colder winter in the area (Hurrell, 1995).

NAO indices have been calculated from as far back as 1860 up to the present using SLP data from Azores and Iceland. Despite a high annual variability, the indices tend to show periods when they are mostly positive and periods when they are mostly negative. The last 25 yr of the 20th century were characterized by an unrecorded series of high positive values (Hurrell, 1995).

Diverse proxy data have been used in order to reconstruct NAO indices back in time, up to 350 yr long for a proxy NAO index from ice accumulation records in Greenland (Appenzeller, 1999). Tree-ring data have also been used in reconstructing NAO indices back to the year A.D.

1523-0430/04 $7.00

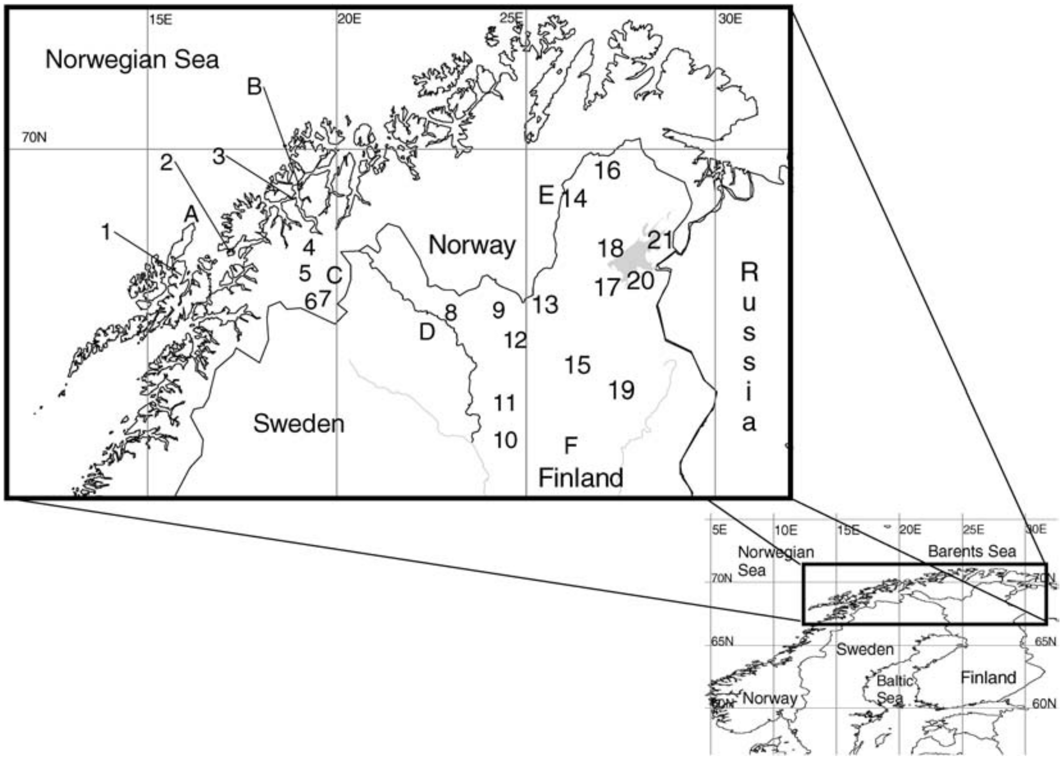

FIGURE 1. Map of northern Fennoscandia. Numbers are locations of the sites, displayed as in Table 1. Letters are locations of the meteorological stations. A: Andenes, B: Tromsø, C: Frihetsli, D: Karesuando, E: Karasjok, F: Sodänkylä.

1700 (Cook et al., 1998). Northern Fennoscandian chronologies have been used in these reconstructions. Some studies have focused on the study of the correlation among NAO indices and Fennoscandia tree rings, finding significant correlations between tree-ring indices and winter and summer NAO indices (D'Arrigo et al., 1993; Lindholm et al., 2001).

AIMS OF THE STUDY

The primary objectives of this research are to:

(1) conduct spatial-temporal comparison of the variability of several chronologies from northern Fennoscandia, on both sides of the Scandes Mountains (67°N–70°N, 15°E–29°E), in order to detect differences in tree growth due to different climatic conditions in the studied area and during the studied period.
(2) analyze the relationships of ring-width chronologies with temperature, precipitation, and NAO indices, and of the evolution of these relationships during the time.

Data

TREE-RING DATA

A network of 21 ring-width chronologies of *Pinus sylvestris* from the north of Fennoscandia on both sides of the Scandes, with latitudes ranging from 67N to 70N and longitudes ranging from 15°E to 29°E, was used. Fourteen of these chronologies have been previously published (Lindholm, 1995, 1996; Kirchhefer, 2000, 2001). Seven chronologies, corresponding to the Finnish Lapland, were built by Mauri Timonen in 2001, and have not yet been published (Table 1, Fig. 1). Tauskjerring/Rønninglia and Devdiselva/Høgskardet are "pairs of chronologies" (site chronologies representing slope aspect).

CLIMATIC DATA

For the studies with mean monthly temperature and monthly precipitation we have selected six meteorological stations distributed evenly in the study area. These stations are Sodankylä, Finland; Karesuando, Sweden; Karasjok, Norway;, Andenes, Norway; Frihetsli (Dividalen), Norway; and Tromsø, Norway. Station names, locations, and lengths of the data records are shown in Table 2 and displayed in Figure 1.

Andenes records are not homogeneous in 1963 due to a relocation of the station. No corrections were made in this case, because this relocation implied a temperature change far smaller than the year-to-year variability (Kirchhefer, 2001). Frihetsli (Dividalen) records have some gaps. Kirchhefer (2000) estimated missing data by taking the precipitation data from the nearby Oeverbygd station. Temperature and precipitation data for Tromsø, Karasjok, Sodankylä, and Karesuando were taken from the NordKlim data set (Tuomenvirta et al., 2001).

There are several NAO indices available, obtained by slightly different calculation methods and from different climate stations (Rogers, 1984; Hurrell, 1995; Jones et al., 1997). In this study we have used the NAO indices obtained by Hurrell (1995). Monthly, seasonal, and annual NAO indices are based on the difference of normalized SLP between Ponta Delgada, Azores, and Stykkisholmur/Reykjavik, Iceland, since 1865 (Hurrell, 1995).

Methods

CHRONOLOGY DEVELOPMENT

Individual measurement series were divided by the values of negative exponential functions or nonascending straight lines to remove the age-related growth trend. The resulting dimensionless indices were averaged to form master chronologies for each of the locations. Negative exponential functions maximize low-frequency variability, and are thus well suited for climatic reconstruction (Cook

TABLE 1

*Scots pine (*Pinus sylvestris *L.) chronology network. Locations of the sampling sites for the pine ring-width chronologies. The number of cores of each chronology and the temporal span of the chronologies are included*

Site	Country	Start	End	Span	Latitude	Longitude	No. of cores	Author
ATLANTIC COAST AND SCANDES								
1 Forfjorddalen	Norway	877	1994	1118	68°48′N	15°44′E	71	A. J. Kirchhefer
2 Stonglandseidet	Norway	1403	1997	595	69°05′N	17°13′E	66	A. J. Kirchhefer
3 Vikran	Norway	1599	1992	394	69°32′N	18°44′E	44	A. J. Kirchhefer
4 Tauskjerring	Norway	1545	1994	450	69°02′N	18°55′E	37	A. J. Kirchhefer
5 Rønninglia	Norway	1620	1994	375	68°58′N	18°55′E	36	A. J. Kirchhefer
6 Høgskardet	Norway	1498	1995	498	68°50′N	19°33′E	36	A. J. Kirchhefer
7 Devdiselva	Norway	966	1992	1027	68°51′N	19°37′E	38	A. J. Kirchhefer
EAST OF THE SCANDES								
8 Karesuvanto	Finland	1698	1992	295	68°29′N	22°09′E	26	M. Lindholm
9 Leppajärvi	Finland	1789	1991	203	68°31′N	23°17′E	35	M. Lindholm
10 Kolari	Finland	1861	2000	140	67°21′N	23°50′E	19	M. Timonen
11 Pakasaivo	Finland	1761	2000	240	67°35′N	24°E	29	M. Timonen
12 Pitkajärvi	Finland	1780	2000	221	68°18′N	24°E	28	M. Timonen
13 Nunnanen	Finland	1786	1991	206	68°24′N	24°31′E	56	M. Lindholm
14 Karasjok	Norway	1803	1992	190	69°35′N	25°38′E	29	M. Lindholm
15 Taatsi	Finland	1682	2000	319	68°09′N	25°46′E	21	M. Timonen
16 Skallovaara	Finland	1711	1991	281	69°48′N	27°10′E	20	M. Lindholm
17 Rlekkovaara	Finland	1755	2000	246	68°25′N	27°16′E	29	M. Timonen
18 Karhunpesäkivi	Finland	1397	1993	597	68°59′N	27°18′E	23	M. Lindholm
19 Lokka	Finland	1773	2000	228	67°47′N	27°42′E	29	M. Timonen
20 Peuravuonon	Finland	1659	1992	334	68°32′N	28°00′E	26	M. Lindholm
21 Kessi	Finland	1789	2000	212	69°05′N	28°50′E	28	M. Timonen

et al, 1990). Residual chronologies, computed after removing autocorrelation from the individual series, were used in all response analysis.

DESCRIPTIVE STATISTICS AND GROWTH VARIATIONS

Expressed Population Signal (EPS), which is a function of the series replication and the mean interseries correlation, was used as a measure of the strength of the common signal within the chronology (Wigley et al., 1984). In order to have EPS values >85% in the entire study period for all chronologies, the period analyzed was set to 1880–1991. Interseries Pearson correlations and evolution of these correlations along a 30-yr overlapping period were also calculated.

Some other descriptive statistics were calculated for each chronology to allow comparisons among the chronologies analyzed in this study as well as to permit comparisons with other dendroclimatic data sets (Fritts, 1976; Briffa and Jones, 1990). These statistics are standard deviation (SD), mean sensitivity (MS), first order autocorrelation (r1), the percentage of variation explained by the first principal component (VARpc1), as well as signal-to-noise ratio (SNR) as a measure of the common variance in a chronology scaled by a measure of the total variance of the chronology (Wigley et al., 1984).

TABLE 2

Meteorological stations used in the study of temperature and precipitation relationships with tree growth

Meteorological station	Latitude	Longitude	Altitude (m a.s.l.)	P (mm) time span	T (°C) time span
Andenes (N)	69°19′N	16°06′E	—	1910–1992	1868–1992
Tromsø (N)	69°39′N	18°56′E	100	1880–1999	1880–1999
Dividalen (N)	68°43′N	19°93′E	228	1912–1993	1922–1992
Karesuando (S)	68°26′N	22°31′E	327	1890–1999	1890–1999
Karasjok (N)	69°28′N	25°31′E	129	1895–1999	1890–1999
Sodankylä (FIN)	67°22′N	26°39′E	179	1908–1999	1908–1999

MULTIVARIATE TECHNIQUES

Cluster (UPGMA, an Agglomerative Hierarchical clustering method that uses Euclidean distances as a measure of dissimilarity) analysis was used as a first multivariate approach to examine the structure of the relationships between the residual tree-ring series.

PCA was performed in order to evaluate the shared variance among residual chronologies. PCAs for successive overlapping periods (1880–1910, 1890–1920, 1900–1930, 1910–1940, 1920–1950, 1930–1960, 1940–1970, 1950–1980, and 1960–1991) and for the whole period (1880–1991) were calculated in order to evaluate the temporal stability of this shared variance (Tardif et al., 2002).

TREE-GROWTH RESPONSES TO CLIMATIC FACTORS

Growth responses to temperature and precipitation were assessed using the data of the six meteorological stations mentioned above together with the indices of six chronologies closest to the meteorological stations: Forfjorddalen (coastal northern Norway) for the meteorological data of Andenes, Dividalen (Inner Troms valleys, Norway) for Frihetsli, and Tromsø (coastal northern Norway) for Vikran (Kirchhefer, 2001); Karesuando (east of the Scandes, Sweden) for Karesuvanto, Karasjok (east of the Scandes, Finnmarksvidda, northern Norway) for Karasjok (Lindholm, 1996), and finally Lokka (Finnish Lapland) for the Sodankylä meteorological data (Table 2).

The climate-growth relationship was assessed by a bootstrap orthogonal regression (Till and Guiot, 1990) on the chronologies and mean monthly temperature, total monthly precipitation, and monthly and seasonal (3 mo) NAO indices from the previous September through the current August (PPP-base; Till and Guiot, 1990). As a simpler alternative to assess these relationships, Pearson correlations were also computed between the ring-width series and the climatic data.

Pearson Correlation coefficients were used in analyzing the relationship between only negative (<zero) NAO index series and the corresponding tree-ring indices. The same was done for only positive

TABLE 3

*Chronology characteristics: expressed population (*EPS*), mean sensitivity (*MS*), standard deviation (*SD*), first order autocorrelation (*rl*), signal-to-noise ratio (*SNR*), and variance explained by the first principal component (*VARpcl*). The common period was set as 1880–1991*

Study site	Eps >85% since	Standard chronology *MS*	Standard chronology *SD*	Standard chronology *r1*	Residual chronology *MS*	Residual chronology *SD*	Common interval: 1880–1991 Detrended series *SNR*	Common interval: 1880–1991 Detrended series *VARpc1*
ATLANTIC COAST AND SCANDES								
1 Forfjorddalen	1242	0.19	0.25	0.53	0.21	0.18	17.74	50.80%
2 Stonglandseidet	1538	0.17	0.23	0.58	0.19	0.16	15.39	50.15%
3 Vikran	1671	0.17	0.25	0.68	0.19	0.17	15.46	48.14%
4 Tauskjerring	1766	0.19	0.26	0.62	0.21	0.19	10.14	43.43%
5 Rønninglia	1705	0.19	0.27	0.63	0.22	0.19	9.47	44.43%
6 Høgskardet	1666	0.16	0.24	0.67	0.19	0.17	6.46	42.36%
7 Devdiselva	1611	0.17	0.23	0.62	0.20	0.17	12.84	52.33%
EAST OF THE SCANDES								
8 Karesuvanto	1740	0.17	0.26	0.70	0.20	0.18	28.84	58.40%
9 Leppajörvi	1858	0.20	0.35	0.76	0.20	0.19	33.30	77.62%
10 Kolari	1871	0.15	0.23	0.67	0.19	0.16	5.01	45.66%
11 Pakasaivo	1865	0.15	0.37	0.83	0.19	0.20	4.97	39.57%
12 Pitköjörvi	1796	0.16	0.26	0.73	0.19	0.17	4.75	48.30%
13 Nunnanen	1796	0.17	0.25	0.69	0.20	0.17	50.00	74.80%
14 Karasjok	1870	0.19	0.33	0.85	0.15	0.15	7.91	42.58%
15 Taatsi	1815	0.16	0.31	0.79	0.19	0.19	8.90	54.00%
16 Skallovaara	1760	0.19	0.31	0.71	0.25	0.21	19.86	55.89%
17 Riekkovaara	1804	0.14	0.25	0.71	0.17	0.16	24.97	53.61%
18 Karhunpesõkivi	1727	0.15	0.26	0.73	0.19	0.17	16.74	52.04%
19 Lokka	1784	0.13	0.29	0.84	0.16	0.15	14.57	49.34%
20 Peuravuonon	1690	0.15	0.26	0.71	0.19	0.17	23.96	52.81%
21 Kessi	1865	0.16	0.24	0.62	0.16	0.15	16.44	46.62%

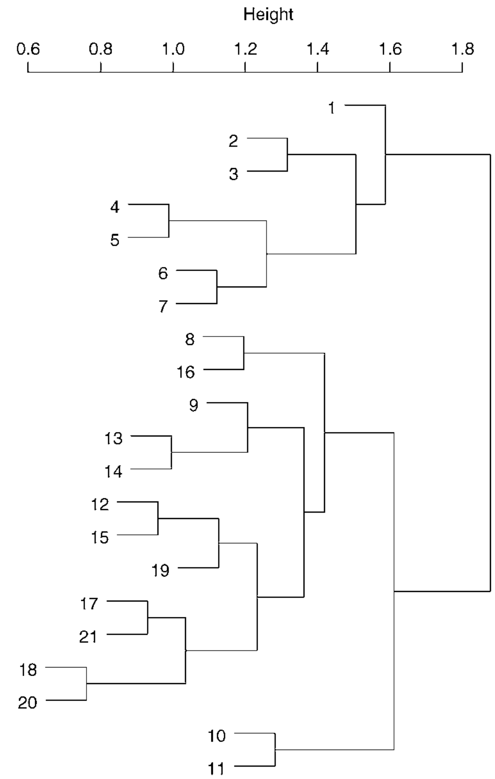

FIGURE 2. Clustering tree resulting from a cluster analysis (UPGMA method) for the 21 residual chronologies of the study. Two groups are well defined, one corresponding to East-of-the-Scandes chronologies (Eastern Subregion), and the other one to Scandes-Atlantic-coast set of chronologies (Western Subregion). Numbers are locations of the sites, displayed as in Table 1.

(>zero) NAO index series. This analysis was conducted with monthly and seasonal NAO index series that showed significant correlation (>99%) with the chronologies.

The purpose of the later analysis was to determine if the correlation with NAO shown by tree growth in Fennoscandia is reflecting both phases of NAO (positive and negative) or, on the contrary, if only specific NAO situations are forcing tree growth.

Results and Discussion

CHRONOLOGY CHARACTERISTICS AND GROWTH VARIATIONS

Chronology statistics are shown in Table 3. No clear spatial trends in chronology statistics were observed across the sampling area at large.

Most of the correlations among standard chronologies taken in pairs are significant, with the mean correlation coefficient for all sites being 0.58. Highest similarity occurred between the standard series from the northeastern area, with 10 pairs having correlation values over 0.8 and 2 over 0.9 (Peuravuonon-Pitkajärvi, $r = 0.902$; Peuravuonon-Karhunpesakivi, $r = 0.922$). Chronologies located in the Scandes and Atlantic coast are also highly correlated, with several pairs showing $r >$ 0.8 (Tauskjerring-Rønninglia, $r = 0.867$; Stonglandseidet-Vikran, $r =$ 0.819; Høgskardet-Devdiselva, $r = 0.843$; Tauskjerring-Devdiselva, $r = 0.813$; Tauskjerring-Høgskardet, $r = 0.825$). Lowest correlations appear among pairs from the two different sides of the Scandes (Rønninglia-Karhunpesakivi, $r = 0.072$; Kolari-Stonglandseidet, $r =$ 0.051; Riekkovaara-Rønninglia, $r = 0.066$). Kolari chronology (east of the Scandes) shows the lowest correlation with the rest of the studied series, with values never reaching 0.4 with any series. This could be due to the fact that it is the youngest and the least replicated chronology (Time span: 1861–2000; 19 series [Table 1]).

The study of the evolution of correlations between chronologies among overlapping successive 30-yr periods shows a drop in the mean interseries correlation during the second half of the 20th century (from r values around 0.65 in the first half of the century to values of 0.5 in the last 30 yr of the period analyzed).

Cluster analysis (Fig. 2) shows two well-defined groups, corresponding to Scandes-and-Atlantic-coast (*Western Subregion* from now on) and East-of-the-Scandes (*Eastern Subregion* from now on) sets of chronologies. However, inside the eastern group, two chronologies, Pakasaivo and Kolari, are separated from the rest, probably because of their anomalous growth pattern in the 1970s. As recommended in multivariate studies, we did not include these two chronologies in the PCA in order to avoid axis deformations due to the presence of outliers (Gauch, 1995).

Principal Component Analysis was computed from the variance-covariance matrix of the 19 chronologies (all except Pakasivo and Kolari) and for the common time period 1880–1991. The explained cumulative variance by the first two principal components is 78.70%. Figure 3 shows a two-dimensional plot for the loadings of the first two PC for each chronology. The first component, explaining 66.33% of variance, is interpreted as an indicator of the similarity among the series, and is positively correlated with all the chronologies. The second component (VARpc2 = 12.36%) is interpreted as a West-East gradient and segregates the chronologies according to their location west or east of the Scandes Mountains, and is positively correlated with the chronologies on the Western Subregion and negatively correlated with the eastern sites.

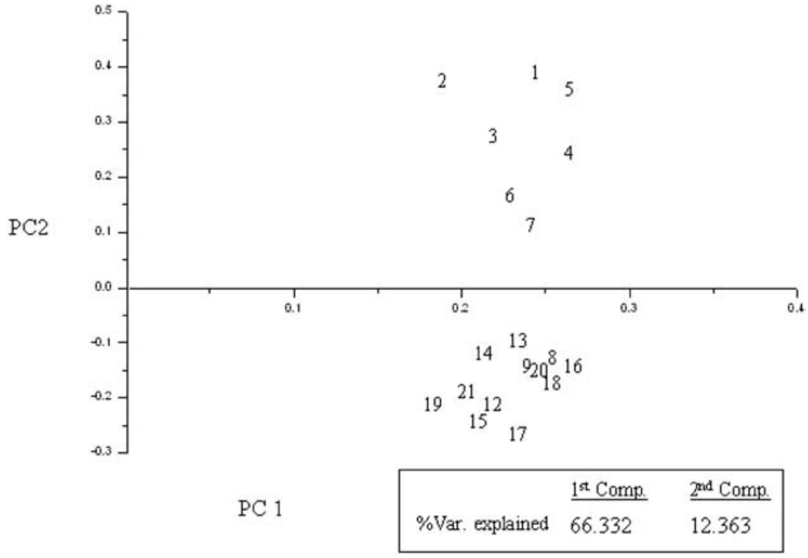

FIGURE 3. Plot of the loadings for each residual series of the two first PC. The scaling of the axis is relative to the Standard Deviation of each PC. The first PC can be interpreted as a common climatic signal, having all the series a positive correlation with it. The second PC, as a difference between the oceanic chronologies (which show positive correlations with it) and the continental chronologies (which are negatively correlated with it). Numbers are locations of the sites, displayed as in Table 1.

The study of the eigenvalues associated to each year of the two PCs for the 19 chronologies yields the following result: years with low eigenvalues for the first PC correspond to years of low radial growth for all the chronologies and years with high eigenvalues correspond to years with large generalized radial growth in the whole area. Years with high and positive eigenvalues for the second PC correspond to wide rings in the Western Subregion chronologies and narrow rings in the Eastern Subregion chronologies, and vice versa (see Table 4 for some specific examples). This confirms the interpretation of the first PC as an indicator of the common signal among all series and of the second PC as an indicator of a west-east gradient that separates chronologies from the two sides of the Scandes.

Results from the PCAs calculated for successive overlapping 30-yr periods indicate that the percentage of variance extracted by the first and second principal components is not constant through time (Fig. 4). The variance held in common (first component) was at its peak at the beginning of the century and has dropped to a minimum in the last period analyzed (1961–1991). This result indicates less common variation in tree-ring indices for the entire study area. Accordingly, the variance explained by the second component, which represents a west-east gradient, has increased during all the period, with a maximum in the last subperiod computed (1961–1991, $VARpc2 = 23.34\%$). This means an intensification of the differences in tree growth between the two sides of the Scandes, and can be interpreted as a strengthening of the west-east (oceanic-continental) climatic gradient in northern Fennoscandia during the last half of the period analyzed. This supports the above-mentioned results of the evolution of correlations among the series.

CLIMATE GROWTH RESPONSE OF SCOTS PINE

Temperature and Precipitation

Bootstrap orthogonal regression coefficients for the period 1923–1991 are shown in Table 5. Only the common general features will be commented.

As expected, the most significant growth-limiting factor is July mean temperature, with positive and significant relationships at all sites. The same result has been found in many studies in the area (Briffa et al., 1988; Lindholm, 1996; Kirchhefer, 2001). August temperature is also significant in Forfjorddalen (northern coastal Norway).

May precipitation has a positive and significant effect on growth at all sites except at Devdiselva (Inner Troms valleys, northern Norway). Precipitation in spring thus seems to be a general limiting factor. The positive response to May precipitation is probably caused by rain induced early snowmelt and soil warming, enabling an early start of the vegetation period (Kirchhefer, 2001).

No clear spatial trends arise from the study of the relationships of chronologies with temperature and precipitation data for the six meteorological stations.

Pearson correlations were also performed (not shown) on temperature and precipitation/series. These results agree with the ones

TABLE 4

Mean residual widths for all the Eastern Subregion chronologies (N = 12) and Western Region ones (N = 7) for the years with maximum and minimum eigenvalues in the two first PCs of the PCA done for the 19 chronologies for the period 1880–1991, and their correspondent standard deviation. In the first axis, years with the highest eigenvalues correspond to years with generalized large radial growth, and years with the lowest eigenvalues correspond to years of low radial growth for all the chronologies. For the second axis, years with high and positive eigenvalues correspond to wide rings in the Western chronologies (in relation with the Eastern chronologies) and narrow rings (in relation with Western chronologies) in the Eastern chronologies, and vice versa

		High eigenvalues 1st PC				Low eigenvalues 1st PC				High eigenvalues 2nd PC			Low eigenvalues 2nd PC		
		1930	1934	1937	1941	1892	1900	1903	1928	1969	1980	1985	1920	1923	1975
Eastern Subregion	Mean index	1.45	1.37	1.37	1.28	0.71	0.73	0.67	0.72	0.96	0.91	1.13	1.18	1.18	1.02
	Std. Dev.	0.12	0.11	0.10	0.05	0.08	0.11	0.07	0.11	0.13	0.06	0.06	0.07	0.08	0.05
Western Subregion	Mean index	1.43	1.26	1.37	1.38	0.67	0.71	0.72	0.80	1.17	1.22	1.48	0.95	0.82	0.74
	Std. Dev.	0.06	0.08	0.10	0.11	0.04	0.07	0.07	0.10	0.10	0.07	0.21	0.09	0.14	0.08

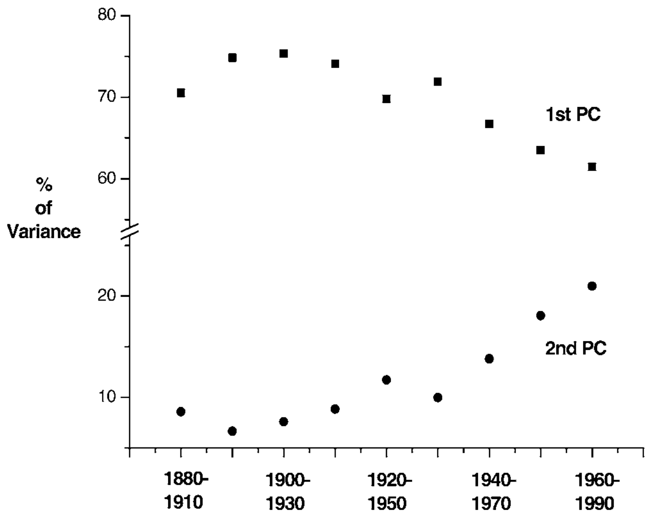

FIGURE 4. Percent of variance expressed by the first and second principal components of PCA made from a matrix with the 19 selected residual chronologies for the subperiods: 1880–1910, 1890–1920, 1900–1930, 1910–1940, 1920–1950, 1930–1960, 1940–1970, 1950–1980, and 1960–1991. For the whole period 1880–1991, the variance explained by the first PC is 66.33% and the variance explained by the second PC is 12.36%.

yielded by bootstrap regression. The bootstrap does not yield significant correlations due to randomness by artificially increasing the number of observations, and as a result there are less significant multiple regression coefficients than correlation coefficients for the same set of data analyzed.

NAO Indices

As seen before, it is possible to separate the chronologies east of the Scandes (Eastern Subregion) from the chronologies on the Scandes and Atlantic coast (Western Subregion), according to different radial growth patterns.

A Principal Component Analysis was performed taking only the seven residual chronologies located on the Western Subregion (Forfjorddalen, Stonglandeiset, Vikran, Tauskjerring, Rønninglia, Devdiselva, and Høgskardet). The first component of this PCA explains the variance held in common among the seven combined chronologies (78.42% of the common variability) and can be interpreted as a regional chronology for the Western Subregion. Another PCA was performed then for the 12 chronologies of the Eastern Subregion. The first PC explains 73.24% of the variance and is also interpreted as a regional chronology for the Eastern Subregion.

Bootstrap regression analyses were conducted separately based on both subregional chronologies and monthly NAO data from the previous September to the current August (Table 6a). The same was done with seasonal (3-mo mean) data from the previous September-October-November (SON) to the current August-September-October (ASO) NAO indices (Table 6b).

Subregional chronologies using PCA were also computed for the two sets of chronologies and the subperiods 1880–1930 and 1931–1991. The variance held in common in these new PCs ranges between 72.48% and 79.79%, so they can also be considered as regional chronologies.

As a control, Pearson correlations (not shown) were computed between NAO series and tree-ring chronologies.

Period 1880–1991: Tree-growth is mostly related (positively) with NAO indices corresponding to the previous early winter (November, December) and to the end of the spring/beginning of the summer (May, June, July) in all the study area (Table 6a).

The individual monthly NAO value best related with the series is May for the East and June for the West, and the most significant 3-mo period is MJJ (May-June-July) (for the Eastern regional chronology). Although NAO is most clearly expressed during the winter (Van Loon and Rogers, 1978), trees are showing strong sensitivity to NAO values representing end of spring/beginning of summer. This season is of extreme importance for the end of their dormancy and the beginning of their vegetation period. Nonbiological proxy data, such as ice cores, might show better correlations with winter NAO values. Positive NAO values at the end of spring imply an increased moist western winds activity. As seen in the relationships with precipitation, a rainy May is highly positively correlated with growth, probably because of rain causing early snow melt, enabling an early start of the vegetation period (Kirchhefer, 2001).

TABLE 5

Response functions based on bootstrap orthogonal regression on residual chronologies and monthly climate data from previous September to current August, for the period 1923–1991. Mean bootstrap correlation coefficients and their standard deviations are shown. When significant at 90% confidence level, mean bootstrap regression coefficients (above) and the ratio mean correlation coefficients/standard deviation (below) are shown for individual months. When this ratio is greater than 1.645, there is 90% of confidence. When the value exceeds 1.96, the degree of confidence is 95%

	Temperature												Precipitation											
	S	O	N	D	J	F	M	A	M	J	J	A	S	O	N	D	J	F	M	A	M	J	J	A
WESTERN SUBREGION																								
Forfjorddalen											0.42	0.24		−0.18				−0.13			0.18			0.19
											5.04	2.81		−1.65				−1.85			1.92			2.1
Vikran		−0.18									0.33					0.17					0.21		−0.17	
		−2.00									3.88					1.71					2.26		−1.90	
Devdiselva							0.23				0.49								0.19					
							2.30				4.20								1.87					
EASTERN SUBREGION																								
Karasjok											0.40			0.18							0.21			
											3.77			1.91							1.86			
Karesuvanto				0.15	0.24						0.40									0.18	0.16			
				1.70	2.50						3.99									1.74	1.72			
Lokka	0.20					−0.20			0.22		0.29										0.17			
	2.06					−2.08			2.03		2.55										1.74			

TABLE 6a

Response functions based on bootstrap orthogonal regression on Eastern and Western subregion chronologies and monthly NAO data from previous September to current August. Mean bootstrap correlation coefficients and their standard deviations are shown. When significant at 90% confidence level, mean bootstrap regression coefficients (above) and the ratio mean correlation coefficients/standard deviation (below) are shown for individual months. When this ratio is greater than 1.645, there is a 90% degree of confidence. When the value exceeds 1.96, the degree of confidence is 95%. The periods analyzed are 1880–1991, 1880–1930, and 1931–1991

	Monthly NAO indices											
	S	O	N	D	J	F	M	A	M	J	J	A
1880–1991												
PC1 East			0.20	0.17					0.24	0.17	0.19	
			2.48	1.91					2.42	1.68	2.24	
PC1 West		0.16								0.18		
		1.84								2.21		
1880–1930												
PC1 East			0.19	0.18					0.25	0.39	0.15	
			2.06	1.68					2.6	3.53	1.64	
PC1 West			0.29						0.22	0.32		
			3.2						1.99	2.5		
1931–1991												
PC1 East			0.23								0.28	
			1.7								2.09	
PC1 West												

The last months of the previous fall (N, D) NAO values are also significant. Significant and positive correlation coefficients of radial growth and December temperatures have been found in this study for most chronologies (Pakasaivo, Kolari, Kessi, Riekkovaara, Pitkäjärvi, Taatsi, Karesuvanto, Karhunpesakivi, Leppajärvi, Nunnanen, Skallovaara, Karasjok, Forfjorddalen, Devdiselva, Høgskardet, and Tauskjerring). Positive NAO indices during the early winter imply a mild beginning of the winter. D'Arrigo et al. (1993) already found that some Scots pine tree-ring series from Fennoscandia were significantly related to winter NAO and Oslo winter temperatures. Rogers and Van Loon (1979) and Rogers (1990) indicate that anomalies in North Atlantic sea-surface temperatures, sea-ice extent and sea-level pressure associated with extreme NAO conditions can persist into the spring and summer months, when climate is exerting a more direct influence on tree growth (Cook et al., 1998).

Subperiods 1880–1930 and 1930–1991: During 1880–1930, subregional chronologies (Eastern and Western) yield the same correlations with NAO indices as described for the whole period 1880–1991. The two tree-growth–sensitive seasons for NAO (end of the spring and previous early winter) are very clearly defined, especially in the monthly data analysis.

However, in the analysis for the subperiod 1931–1991, no pattern of correlation between NAO indices and subregional chronologies is observed. Some significant coefficients appear, only in the Eastern subregion chronology. When appearing, significant coefficients are stronger than during the first period (previous November and July), but compared with the first period analyzed, a drop in the NAO-series relationship strength is evident. This drop is strongest in the Western subregion chronology. Pearson correlations between individual chronologies and NAO series (not shown) agree with these results.

In their study of NAO dynamics recorded in Greenland Ice cores, Appenzeller et al. (1998) used a Morlet wavelet analysis. The observed power spectrum of the proxy index suggested that the NAO is an intermittent climate oscillation characterized by temporally active (coherent) and passive (incoherent) phases. Atmosphere-ocean interaction on the typical time scales of 5 to 15 yr might occur during active phases, although spatially coherent phases still might exist (Appenzeller et al., 1998). Despite noting that there is a possibility that the proxy NAO index simply represents stochastic variability, they identified as very active NAO phases the periods 1870–1900 and 1900–1930, while the period 1960 onward is a weaker phase. It is noteworthy to consider the similarity between high NAO indices/radial–growth relationship values during active NAO phases and the very low NAO indices/radial–growth relationship during the passive NAO phases.

TABLE 6b

Response functions based on bootstrap orthogonal regression Eastern and Western chronologies and seasonal NAO data from previous September-October-November (SON) to current August-September-October (ASO). Mean bootstrap correlation coefficients and their standard deviations are shown. When significant at a 90% confidence level, mean bootstrap regression coefficients (above) and the ratio mean correlation coefficients/standard deviation (below) are shown for individual months. When this ratio is greater than 1.645, there is a 90% degree of confidence. When the value exceeds 1.96, the degree of confidence is 95%. The periods analyzed are 1880–1991, 1880–1930, and 1931–1991

	Seasonal NAO indices												
	Year	SON	OND	NDJ	DJF	JFM	FMA	MAM	AMJ	MJJ	JJA	JAS	ASO
1880–1991													
PC1 East		0.12	0.12							0.2			
		1.64	1.88							2.16			
PC1 West		0.15	0.17				0.13						
		1.84	2.27				1.75						
1880–1930													
PC1 East									0.23	0.21	0.21		
									2.12	1.77	1.86		
PC1 West		0.29							0.22			−0.26	
		2.53							2.12			−2.28	
1931–1991													
PC1 East													
PC1 West							0.23						
							2.3						

TABLE 7

Significant Pearson correlations between residual chronologies and only positive (>0) or only negative (<0) NAO indices series. PC1E, as PC1 East in Table 6. PC1W, as PC1 West in Table 6. Numbers marked with a plus (+) have a degree of confidence >95%, and those marked with an asterisk (*) have a degree of confidence >99%

	NAO indices											
	November		December		NDJ		May		June		AMJ	
Sites	>0	<0	>0	<0	>0	<0	>0	<0	>0	<0	>0	<0
Eastern Subregion												
Pakasaivo		.26+	.28+		.29+			.40*		.24+		
Kolari								.23+		.24+		.23+
Kessi	.27+		.29+		.35*			.32*		.32*		.28+
Riekkovaara	.35*		.28+		.31*			.24+		.26+		.34*
Pitkäjärvi	.34*		.38*		.32*		.24+	.32*		.29+		.33*
Taatsi	.29+	.27+	.37*		.28+							.32*
Lokka							.29+	.24+		.23+		.27+
Karesuvanto	.26+		.31*		.34*			.33*		.24+	.24+	.36*
Karthunpesakivi	.38*	.31+	.25+		.32*			.23+				.32*
Leppajärvi	.23+		.25+		.33*			.40*				
Nunnanen			.30+		.35*			.41*		.28+	.23+	.28+
Peuravuonon		.27+	.31*		.34*			.30+	.25+	.30+	.25+	.45*
Skallovaara					.35*			.33*		.28+		.36*
Karasjok	.29+	.31+	.22+		.23+			.35*				.28+
PC1E	.30+	.26+	.32*		.34*			.32*		.29+		.27+
Western Subregion												
Vikran					.24+							.34*
Stonglandseidet												
Fortjorddalen	.26+				.26+						.23+	.27+
Devdiselva					.27+			.23+				.26+
Hogskardet								.24+				.30+
Ronninglia					.22+							
Tauskjerring					.30*							.23+
PC1W					.27+						.24+	
No. of years involved	61	50	61	51	63	48	53	57	54	56	54	56

We also calculated the correlations between a subset of >zero NAO indices and the tree-ring series corresponding to the years in which NAO values are only positive for different NAO month and season indices. The objective was to find out if correlations of NAO indices with chronologies are due to both positive and negative NAO situations or, on the contrary, only specific NAO situations are limiting tree growth. The same was done for <zero NAO series. The resulting series are formed by years which are ordered in time but that are not necessarily contiguous. As we are working with residual chronologies and there is no autocorrelation within them, it is possible to split the years of the series and look at the correlation of the newly created tree-ring series with the newly created >zero or <zero NAO series.

The same analysis was performed using the Western and Eastern subregional chronologies previously defined.

The results of this analysis for November, December, and November-December-January (NDJ) (previous early winter); and for May, June, and April-May-June (AMJ) (spring) are displayed in Table 7. Positive correlations of previous early winter NAO indices and chronologies are mostly found in >zero NAO series. When NAO is positive at the previous early winter, the climatic patterns in northern Fennoscandia (mild beginning of winter) enhance tree growth in the next growth season, while when NAO at the previous early winter is negative, the climatic patterns in northern Fennoscandia (nonmild beginning of winter) do not affect tree growth in the next growing season.

On the other hand, positive correlations of spring NAO indices and chronologies are mostly found in <zero NAO series. NAO being negative at the spring in northern Fennoscandia can limit tree growth, while positive NAO values at the spring do no affect tree growth. A more detailed explanation of this would relate negative NAO springs with later snowmelt and later beginning of the vegetation period (as Kirchhefer [2001] proposes). During negative NAO springs, snowmelt timing constitutes a limiting factor for tree growth. Higher than normal temperatures associated with positive NAO springs often favor an early snowmelt. Under these conditions, ground starts to warm up earlier than during negative NAO springs. Low spring temperatures in soil may limit tree growth in the next summer. Soil temperatures might not be a limiting factor if they are high enough before trees start to be active, as probably happens during positive NAO springs, which are uncorrelated with tree growth. It is a widely known ecological rule that when a factor is not limiting anymore, other limiting factors appear (Fritts, 1976).

The same method was done using the PC representing the eastern set of chronologies and the PC representing the western one giving similar results, with a much better fit for the eastern set of series.

Conclusions and Significance

(1) In accordance with previous studies (Briffa et al., 1990; Lindholm, 1996), the main limiting climatic factor in the northern Fennoscandian forests is July temperature. May precipitation is another key factor for tree growth, and it is caused by rain inducing early snowmelt and soil warming, enabling an early start of the vegetation period (Kirchhefer, 2001).

(2) Although having a major common climatic signal, tree-ring chronologies from both sides of the Scandes Mountains during the common period 1880–1991 show growth differences, detectable by the study of (1) standardized series, (2)

correlations among the chronologies along time, and (3) multivariate comparisons.

(3) The second half of the period studied, corresponding to 1931–1991, is characterized by an enhancing of the east-west differences in northern Fennoscandia. There is an increase in the variance explained by the second component of the PCA of the residual series, which represents a strengthening of radial growth differences between the Western and the Eastern Subregions. These enhanced growth differences are also detected in the study of the evolution of the correlations among chronologies.

(4) Northern Fennoscandia forests are most sensible to previous early winter and end of the spring-summer NAO indices. They show significant positive relationships with these NAO season values.

(5) During the first half of the period analyzed (1880–1930), NAO indices and residual chronologies are very highly correlated, while in the second half (1931–1991), the correlations of radial growth with NAO indices drop, especially in the west.

(6) Positive previous early winter NAO indices enhance tree growth in the next growing season, while negative previous early winter NAO indices do not have any correlation with tree growth. On the other hand, positive NAO spring values are not correlated with radial growth, while negative NAO spring values show a significant correlation with them.

Multivariate techniques (PCA in particular) have proven to be very useful in tree-ring studies when applied to a climatic gradient. The combined interpretation of loadings, eigenvalues and cumulative variance expressed by the analysis has allowed a detailed description of the information tree rings in the area contain about the climatic gradient. The use of the 1st PC series as a regional chronology was possible due to the high common variance it expresses and to the fact that all chronologies have positive loadings with the 1st PC. The eigenvaules associated to each year of the PC series can be used as a way to identify pointer years. For the 1st PC, years of extreme growth for the whole area correspond to extreme eigenvalues. For the 2nd PC, it is possible to identify what could be called relative or gradient pointer years: that is, years that are conspicuous because of being wide (narrow) in one side of the gradient and narrow (wide) in the other extreme of it. Such relative pointer years could not be detected by classical pointer year methods, and will be further analyzed in future studies, as they contain the clues to describe situations where the climatic gradient peaks.

When studying climatic gradients, it is basic to take into account that these gradients fluctuate, they are time variable, and they can increase or decrease in intensity during the period under study. This is why an analysis by subperiods is strongly recommended and widely used (Tardif et al. 2003). In this study, the subperiod analysis of the relationships between chronologies along the gradient has revealed a general decrease in the variability they hold in common, especially in the second half of the 20th century. This decrease is coinciding with a significant loss of correlation between the chronologies and the NAO indices. In a study on wood density/air temperature relationships, Briffa et al. (1998) already described a loss of sensitivity of wood density to temperature changes during the late 20th century. To determine whether this is a result of NAO active/passive phase dynamics, a consequence of an anthropogenic induced climatic change, or if it is caused by a combined effect of both, is something beyond the scope of this paper, but it is without doubt one of the main lines of our future research in this topic. Identifying which of the NAO-affected climatic parameters has been changing in the area will help us to answer these questions. However, the change is most probably affecting not one but many combined precipitation and temperature parameters.

Describing and understanding such temporal changes in the strength with which NAO affects tree rings in the area is of vital importance when using tree rings as proxy data in dendroclimatic reconstructions.

This study also reveals the fact that NAO/tree-ring relationships are not continuous along all range of NAO values. It is important to realize that NAO can affect tree growth in a given season only if it is positive (i.e. end of previous fall) or negative (i.e. end of spring/beginning of summer). That is, the combined effects of NAO on temperature and precipitation over the area are limiting tree growth only in certain NAO situations, whereas in other NAO phases, its effects over tree growth for a given season are simply nonexistent.

Acknowledgments

The work was funded by the Academy of Finland (grant 50713 to Matti Eronen) and by a CIMO (Centre for International Mobility) grant given by the Finnish Ministry of Education from November 2001 to May 2002. We are grateful to Samuli Helama for his support and help. On the Catalan side, we want to strongly thank Oriol Bosch for all his advice and teaching. We also thank Dr. L. Harder and Dr. Isabelle Logan for their comments.

References Cited

Appenzeller, C., 1999: Reconstruction of decadal climate variability. North Atlantic Oscillation. Swiss Climate Summer School, Climate and Environmental Physics, University of Bern.

Appenzeller, C., Stocker, T. F., and Anklin, M., 1998: North Atlantic Oscillation dynamics recorded in Greenland ice cores. *Science,* 282: 446–449.

Barry, R. G., 1992: *Mountain Weather and Climate.* 2nd ed. London: Routledge. 402 pp.

Briffa, K. R. and Jones, P. D., 1990: Basic chronology statistics and assessment. *In* Cook, E. and Kairiukstis, L. (eds.), *Methods of Dendrochronology: Applications in The Environmental Sciences.* Dordrecht: Kluwer Academic Publishers, 137–152.

Briffa, K. R., Bartholin, T. S., Eckstein, D., Jones, P. D., Karlén, W., Schweingruber, F. H., and Zetterberg, P., 1990: A 1400-year tree-ring record of summer temperatures in Fennoscandia. *Nature,* 346: 434–439.

Briffa, K. R., Jones, P. D., Pilcher, J. R., and Hughes, M. K., 1988: Reconstructing summer temperatures in northern Fennoscandia back to A.D. 1700 using tree-ring data from Scots pine. *Arctic and Alpine Research,* 20: 385–394.

Briffa, K. R., Schweingruber, F. H., Jones, P. D., Osborn, T. J., Shiyatov, S. G., and Vaganov, E. A., 1998: Reduced sensitivity of recent tree-growth to temperature at high northern latitudes. *Nature,* 391: 678–682.

Cook, E. R., Briffa, K. R., Shijatov, S. G., and Mazepa, V., 1990: Tree-ring standardization and growth-trend estimation. *In* Cook, E. and Kairiukstis, L. (eds.). *Methods of Dendrochronology: Applications in the Environmental Sciences.* Dordrecht: Kluwer Academic Publishers.

Cook, E. R., D'Arrigo, R. D., and Briffa, K. R., 1998: A reconstruction of the North Atlantic Oscillation using tree-ring chronologies from North America and Europe. *The Holocene,* 8: 9–17.

D'Arrigo, R. D., Cook, E. R., Jacoby, G. C., and Briffa, K. R., 1993: NAO and sea surface temperature signatures in tree-ring records from the North Atlantic sector. *Quaternary Science Reviews,* 12: 431–440.

Fritts, H. C., 1976: *Tree Rings and Climate.* London: Academic Press. 567 pp.

Gauch, H. G., Jr., 1995: *Multivariate Analysis in Community Ecology.* Cambridge: Cambridge University Press. 298 pp.

Hurrell, J. W., 1995: Decadal trends in the North Atlantic Oscillation: regional temperatures and precipitation. *Science,* 269: 676–679.

Jones, P. D., Jonsson, T., and Wheeler, D., 1997: Extension using early instrumental pressure observations from Gibraltar and SW Iceland to the North Atlantic Oscillation. *International Journal of Climatology,* 17: 1433–1450.

Kirchhefer, A. J., 1999: Pine growth and climate AD 1800–1992 along a transect across the Scandes at 69°N. *In* Kirchhefer, A .J., *Dendroclimatology on Scots Pine (*Pinus sylvestris *L.) in Northern Norway.* Department of Biology, Faculty of Science, University of Tromsø, Norway, 1-25.

Kirchhefer, A. J., 2000: The influence of slope aspect on radial increment of *Pinus Sylvestris* L. in northern Norway and its implications for climate reconstruction. *Dendrochronologia,* 18: 27–40.

Kirchhefer, A. J., 2001: Reconstruction of summer temperature from tree rings of Scots pine, *Pinus sylvestris* L., in coastal northern Norway. *The Holocene,* 11: 41–52.

Linderholm, H. W., Solberg, B. Ø., and Lindholm, M., 2003: Tree-ring records from central Fennoscandia: The relationship between tree growth and climate along and East-West transect. *The Holocene,* 13(6): 887–895.

Lindholm, M., 1995: Reconstruction of growing season temperatures from ring-width chronologies of Scots pine at the northern forest limit in Fennoscandia. Licentiate's dissertation. University of Joensuu, Faculty of Natural Sciences, Department of Biology. 125 pp.

Lindholm, M., 1996: Reconstruction of past climate from ring-width chronologies of Scots pine (*Pinus sylvestris* L.) at the northern forest limit in Fennoscandia. Academic dissertation. University of Joensuu, Faculty of Natural Sciences, Department of Biology. 169 pp.

Lindholm, M., Eggertsson, Ó., Lovelius, N., Raspopov, O., Shumilov, O., and Läänelaid, A., 2001: Growth indices of North European Scots pine record the seasonal North Atlantic Oscillation. *Boreal Environment Research,* 6: 1–10.

Rogers, J. C., 1984: The association between the North Atlantic Oscillation and the Southern Oscillation in the Northern Hemisphere. *Monthly Weather Review,* 112: 1999–2015.

Rogers, J. C., 1990: Patterns of low-frequency monthly sea level pressure variability (1899–1986) and associated cyclone frequencies. *Journal of Climate,* 3: 1364–1379.

Rogers, J. C. and Van Loon, H., 1979: The seesaw in winter temperatures between Greenland and northern Europe. Part II: Some oceanic and atmospheric effects in middle and high latitudes. *Monthly Weather Review,* 107, 509–519.

Tardif, J., Camarero, J. J., Ribas, M., and Gutiérrez, E., 2003: Spatiotemporal variability in tree growth in the Central Pyrenees: climatic and site influences. *Ecological Monographs,* 73: 241–257.

Till, C. and Guiot, J., 1990: Reconstruction of precipitation in Morocco since 1100 AD based on *Cedrus atlantica* tree-ring widths. *Quaternary Research,* 33: 337–351.

Tuhkanen, S, 1880: Climatic parameters and indices in plant geography. *Acta Phytogeographica. Suecica*, 67. Svenska Vaxgeografiska Sallekapet, Uppsala.105 pp.

Tuomenvirta, H., Drebs, A., Førland, E., Tveito, O. E., Alexandersson, H., Laursen, E. V., and Jónsson, T., 2001: Nordklim data set 1.0 - description and illustrations. DNMI klima 08/01. 27 pp.

Van Loon, H. and Rogers, J. C., 1978: The seesaw in winter temperatures between Greenland and Northern Europe. Part I: General description. *Monthly Weather Review,* 106: 296–310.

Wigley, T. M. L., Briffa, K. R., and Jones, P. D., 1984: On the average value of correlated time series, with applications in dendroclimatology and hydrometeorology. *Journal of Climate and Applied Meteorology,* 23: 201–221.

Ms submitted April 2003